Fengshuo He
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: hefs@hrbeu.edu.cn

Tong Lu
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: lutong98@hrbeu.edu.cn

Zhenjia Pan
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: pzj@hrbeu.edu.cn

Yu Niu
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: niuyudeyouxiang@126.com

Gongjie Zhou
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: 3490452733@qq.com

Yong Lu[1]
College of Power and Energy Engineering,
Harbin Engineering University,
Harbin, Heilongjiang 150001, China
e-mail: luyongheu@hrbeu.edu.cn

Thermodynamic Analysis and Optimization for Exhaust Energy Splitting: An Innovative Method of Improving Exhaust Energy Grade for the Low-Speed Marine Diesel Engine

In this study, a method for improving the exhaust energy grade called exhaust energy splitting is proposed. During the exhausting process of a low-speed marine diesel engine, the exhaust energy splitting is used to split and recover the exhaust in the early stage and the sweeping gas in the late stage separately. GT-Power software and Flowmaster software are used to co-simulate and design the exhaust energy splitting system. Through exergy analysis of the exhaust piping system before and after the energy splitting, the exergy efficiency of the system increases by about 0.47–4.92%, and the optimal splitting phase is around −115 deg. At the same time, the exhaust splitting system is optimized from the perspectives of heat exergy and kinetic energy exergy, and the results show that the exergy efficiency of the optimized exhaust piping system improves by 0.2–2%. This paper demonstrates the feasibility of exhaust energy splitting through exergy analysis. [DOI: 10.1115/1.4056301]

Keywords: low-speed marine diesel engine, exergy analysis, exhaust energy, energy splitting, waste heat recovery, GT-Power, Flowmaster, energy efficiency, energy systems

1 Introduction

The fuel energy utilization efficiency of modern large diesel engines is about 50% and the rest of the energy is lost to the environment by wastewater, exhaust gas, and other cooling media and radiation heat exchange processes [1–5]. Utilizing the waste energy can significantly improve the efficiency of the marine engine and reduce transportation costs while meeting the CO_2 emission limits set by the International Maritime Organization [6–9]. Currently, waste heat recovery systems (WHR) are usually used to utilize the waste energy. For most marine engine waste heat recovery systems, increasing the exhaust temperature of the engine will increase the efficiency of the waste heat recovery system [10–12]. At present, controlling the combustion phase is mainly used to improve the exhaust temperature, i.e., to control the engine combustion to increase the exhaust temperature. However, this method increases the fuel consumption of the engine and reduces the output power of the engine. Thus, controlling the combustion phase sacrifices the engine performance [13]. Therefore, the "exhaust energy splitting" technology is proposed.

Normally, the low-speed diesel engine discharges the exhaust and the sweeping gas into the collecting pipe uniformly for waste heat recovery during the whole process of the exhaust valve opening. The exhaust in the early stage of the exhausting process has high temperature, high pressure, and large flow. While the sweeping gas in the late stage of the exhausting process has low temperature, low pressure, and small flow. So, the sweeping gas can pull down the overall temperature and pressure of the exhaust and reduce the exhaust energy grade. Then improving the efficiency of the waste heat recovery system becomes difficult. The exhaust energy splitting is a method for waste heat recovery which splits the exhaust and the sweeping gas in the exhausting process and recovers them separately, i.e., the exhaust enters the high-temperature collecting pipe and the sweeping gas enters the low-temperature collecting pipe. Exhaust energy splitting can improve the energy grade of the exhaust and truly realize the "optimal use of heat". For low-speed diesel engine, the exhaust with high-grade heat energy will be uniformly sent to high-temperature collecting pipe, and it is suitable for steam turbine power generation systems, diesel engine compound power turbines, and other systems. And the sweeping gas with low-grade heat energy can be used as organic Rankine cycle (ORC) heat source or heat source for domestic water. Since the exhaust energy splitting technology does not change the combustion process of the engine, it can increase the exhaust heat grade without sacrificing the power of the engine, and thus improve the efficiency of the waste heat recovery system.

At present, the main technical means of waste heat recovery and utilization are Rankine cycle system, seawater desalination, and waste heat refrigeration [14]. Durmusoglu et al. proposed an organic Rankine cycle exhaust gas waste heat recovery system for container ships and analyzed the system by energy efficiency and thermal efficiency. The analysis results showed that the system can save energy by 17.1%, the energy utilization rate of the system is 58%, and the thermal efficiency is 56% [15]. Yang optimized a cross-critical Rankine cycle waste heat recovery system for

[1]Corresponding author.

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a marine diesel engine, and used different working substances to analyze the effect on the system. The results showed that the cost of R236fa is less than other working substances, and R1234fy has the lowest critical temperature. That paper also proposed a cross-critical Rankine cycle system with dimensionless optimal pressure ratio and optimal temperature ratio [16]. Gude et al proposed a concept of using exhaust waste heat from diesel engines, waste heat from cylinder liner water, waste heat from spent steam after the turbine in the power cycle, and latent heat of condensation from the condenser to produce fresh water. The results showed that with the use of exhaust gas driven multi-effect evaporative desalination plant, the operating cost is nearly zero, while the thermal efficiency of the diesel engine power system can be as high as 40–80% [17]. Maheswari et al analyzed an experiment of using thermal energy from diesel engine exhaust gas to desalinate seawater. The results showed that the use of horizontal tube evaporator to absorb diesel exhaust heat does not affect the performance of the engine. And the experiment can desalinate 3 L of seawater per hour which greatly reduces thermal pollution [18]. Aly et al. used diesel exhaust waste heat as energy source to drive a diffusive absorption freezer and investigated its performance. The results showed that the cooling performance coefficient is maximum and the cooling temperature is the lowest when the temperature of waste heat provided to the engine is 215–230 °C, and the system can recover 9% of the waste heat [19]. All the study above just develops and optimizes the thermal systems. They neglect the study of improving the heat source quality, which is the key to affecting the energy efficiency of the waste heat recovery system. Therefore, the exhaust energy splitting is proposed in this study.

The technology of exhaust energy splitting is yet to be improved. Although the exhaust temperature of high-temperature exhaust pipe is increased after splitting, the exhaust flowrate of high-temperature exhaust pipe is lower than before. In other words, the energy grade of the exhaust in the high-temperature exhaust pipe increases, but at the same time, the quantity of energy decreases. Therefore, in this study exergy analysis is used to quantitatively evaluate the exhaust energy splitting technology.

In the exhaust process of low-speed diesel engines, a large amount of exergy loss will be caused by the mixing of high-temperature exhaust gas and low-temperature sweeping gas. Because the experiment of low-speed diesel engine exhaust energy splitting is difficult and its cost is high, simulation method is used to prove the feasibility of the exhaust energy splitting. And the data obtained from simulation can support the subsequent optimization of exhaust piping system. Combined with the proposed exhaust energy splitting method for low-speed diesel engine, this study uses GT-Power software and Flowmaster software for co-simulation to establish the exhaust energy splitting model and obtain the relevant parameters at the outlet of the exhaust pipe of low-speed diesel engine after splitting. Then through the exergy analysis of the exhaust piping system, the parameters of the exhaust piping system are optimized.

2 Simulation Model Building and Validation

2.1 Simulation Model of Exhaust Piping System. In this paper, a low-speed marine two-stroke diesel engine is modeled and validated using GT-Power software to provide the correct boundary parameters for simulation in Flowmaster software. The main parameters of the low-speed diesel engine are shown in Table 1, and the GT-Power simulation model of the low-speed diesel engine is shown in Fig. 1.

Table 1 Main parameters of the low-speed diesel engine

Parameter name	Value
Cylinder bore	340 mm
Stroke	1600 mm
Compression ratio	19.8
Rated power	4896 kW
Rated speed	157 r/min
Firing order	1-6-2-4-3-5

The cylinder pressure curve of the simulation model and the cylinder pressure curve obtained from the experiment under 100% load of operating condition are validated as shown in Fig. 2.

Meanwhile, the whole engine's main performance parameters obtained from experiment and simulation under 100% load and 75% load of operating condition are validated, i.e., brake power, brake specific fuel consumption, mass flowrate, exhaust temperature before turbine, and exhaust pressure before turbine. The results with experiment uncertainty of 200 cycles are shown in Fig. 3.

From Fig. 2, it can be seen that the two curves are greatly consistent throughout the working cycle. And as the results shown in Fig. 3, the error rates between experiment and simulation are within 2%, except the error rate of exhaust temperature before turbine which is 3.7% under 100% load and 4.3% under 75% load, this is due to the error of temperature sensor measurement. The simulation model is validated accurately according to Figs. 2 and 3.

And the Flowmaster simulation model of the low-speed diesel engine exhaust piping system is shown in Fig. 4. Table 2 shows the setting of the exhaust piping parameters in Flowmaster.

Comparison of Flowmaster simulation results and GT-Power simulation results for the exhaust line outlet is shown in Table 3.

Table 3 shows that the error rate of the results obtained by Flowmaster and GT-Power is within 5%, so the Flowmaster simulation model of the exhaust piping system can be used for subsequent simulation studies.

2.2 Simulation Model of Exhaust Piping System After Energy Splitting. Based on the simulation model of the exhaust system of the low-speed diesel engine, the model of the exhaust piping system after energy splitting in Flowmaster is shown in Fig. 5.

In this model, the energy splitting is achieved through a pair of split valves. Therefore, the focus of achieving energy splitting is to properly control the opening and closing of the high-temperature and low-temperature valves. The opening and closing of the split valve in Flowmaster software are set by inputting the lift of the split valve at different times, i.e., the opening curve of the split valve. The exhaust valve of the low-speed diesel engine is closed at −95 deg. In this study, the splitting phases are set at 15 deg, 20 deg, 25 deg, 30 deg, 35 deg, 40 deg, and 45 deg before the exhaust valve is closed, i.e., the splitting phases are −110 deg, −115 deg, −120 deg, −125 deg, −130 deg, −135 deg, and −140 deg to carry out the simulation of energy splitting and study the law of exhaust parameters in the corresponding cases.

3 Exergy Analysis Method of Exhaust Piping System

In the calculation of the exhaust exergy of the low-speed diesel engine, because the change of the working substance position can be ignored, so the working substance potential energy exergy can be ignored. Then the calculation of the exhaust mechanical exergy of the low-speed diesel engine can only calculate the kinetic energy exergy of the working substance and ignore the potential energy exergy. And because the temperature of the exhaust pipeline is high, so the difference between the temperature of the external wall of the exhaust pipeline and the ambient temperature is very large. Due to convection heat transfer and radiation heat transfer, part of the heat will be lost to the outside environment. This part of the heat also contains a certain amount of exergy which is called heat exergy. Therefore, this paper focuses on the enthalpy exergy, kinetic energy exergy, and heat exergy of the working substance.

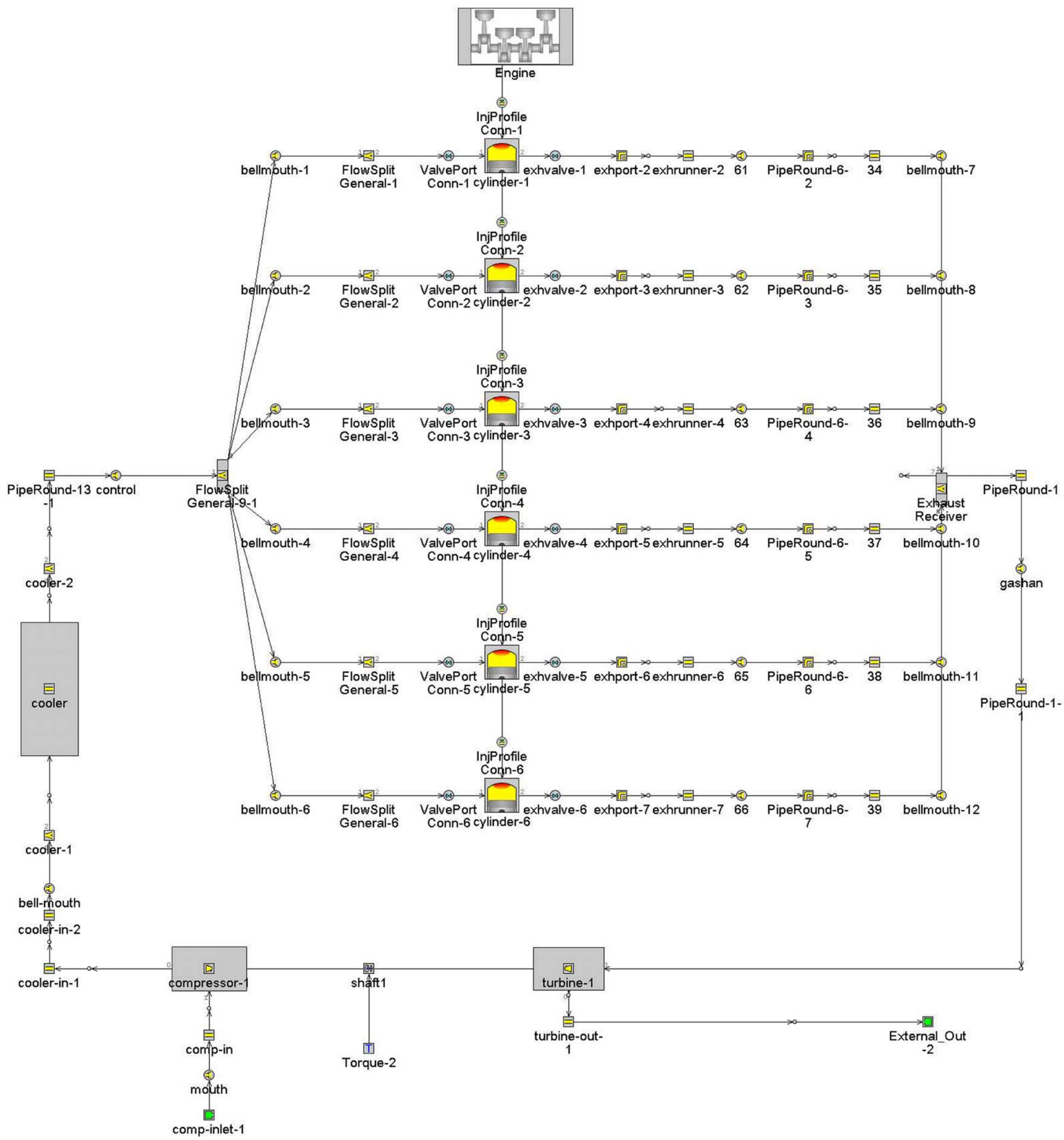

Fig. 1 GT-Power simulation model

3.1 Exergy Calculation Method. For a steady flow open system, the maximum useful work it makes externally can be expressed as [20–22]

$$w_s + \int \delta w = (h - h_0) - T_0(s - s_0) + \frac{1}{2}c^2 + gz \tag{1}$$

where h_0 is ambient enthalpy, h is working substance enthalpy, T_0 is ambient temperature, s_0 is ambient entropy, s is working substance entropy, c is working substance speed, and z is working substance height in gravitational field.

According to the definition of exergy, this part of useful work is the maximum useful work done to the outside world when the unit steady flow working substance is in thermodynamic equilibrium with the system through a reversible thermodynamic process, which is called the physical exergy of the unit steady flow working substance, and can be expressed as

$$\mathrm{e} = (h - h_0) - T_0(s - s_0) + \frac{1}{2}c^2 + gz \tag{2}$$

In most cases, the kinetic energy exergy and potential energy exergy of the working substance are negligible, so the physical exergy of the working substance can be simplified as

$$\mathrm{e} = (\mathrm{h} - h_0) - T_0(s - s_0) \tag{3}$$

The physical exergy at this point is called the enthalpy exergy of the steady flow working substance.

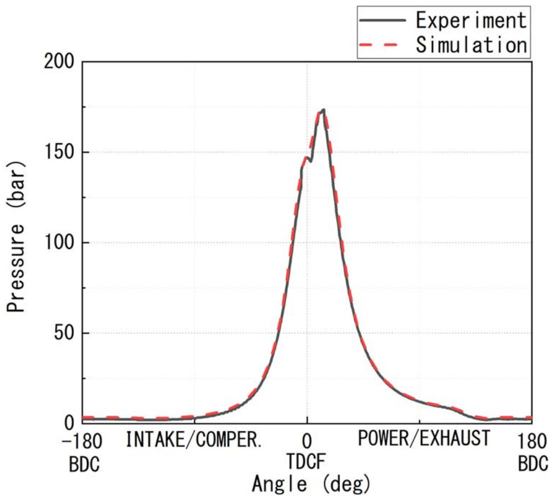

Fig. 2 Validation of the cylinder curve

Then the calculation of the enthalpy exergy of the exhaust system can be expressed as

$$E_H = q_m t[h - h_0 + T_0(s - s_0)] \tag{4}$$

where q_m is working substance mass flow.

The mechanical energy of the system consists of two main components: kinetic energy and potential energy. According to the second law of thermodynamics, mechanical energy can all be converted into different forms of work under certain circumstances. So, the mechanical energy of the system is theoretically all exergy, called mechanical exergy. While the kinetic energy and potential energy in mechanical energy are also exergy called kinetic energy exergy and potential energy exergy. Based on the aforementioned theory, it can be seen that the calculation methods of mechanical energy exergy, kinetic energy exergy, and potential energy exergy are the same as those of mechanical energy, kinetic energy, and potential energy, which can be expressed as

$$\text{Kinetic energy exergy} \quad E_K = \frac{1}{2}mc^2 \tag{5}$$

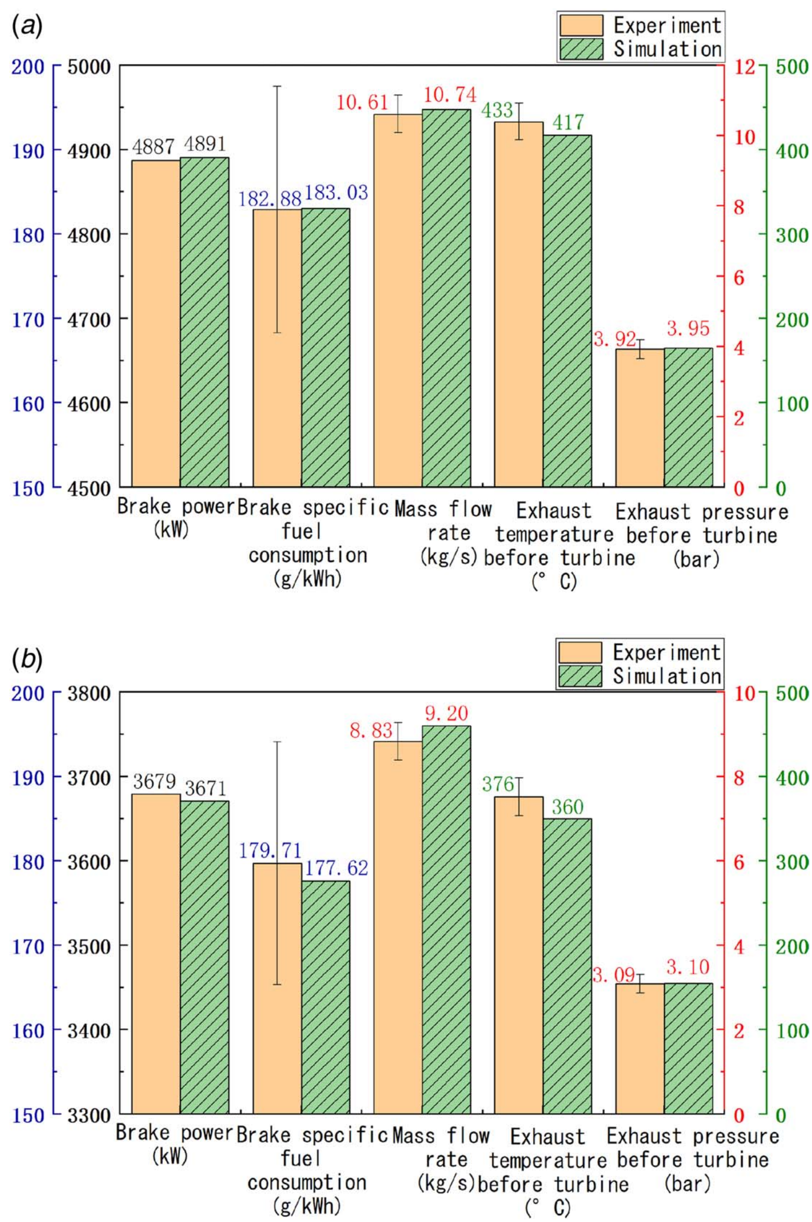

Fig. 3 Validation of the whole engine's main performance parameters obtained from experiment and simulation: (*a*) 100% load and (*b*) 75% load

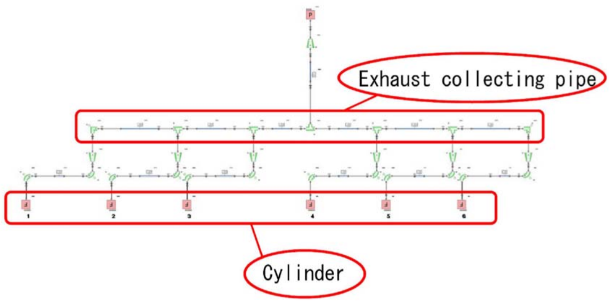

Fig. 4 Flowmaster simulation model of exhaust piping system

Table 2 Setting of the exhaust piping parameters in Flowmaster

	Inlet diameter (mm)	Outlet diameter (mm)	Length (mm)	Angle (°)
Exhaust manifold	146.3	158	262.58	90
	158	158	266	—
	152	152	299.24	45
	152	214	350	—
Exhaust collecting pipe	734	734	3600	—
Exhaust collecting pipe	554	485	265	—
connecting to turbine	425	425	356	—

Table 3 Comparison of the exhaust pipeline outlet parameters simulation results

	Exhaust temperature (K)	Exhaust mass flowrate (kg/s)	Exhaust pressure (bar)
Flowmaster	604.54	9.22	3.02
GT-Power	618.92	9.38	3.08
Error rate	−2.4%	−1.7%	−1.9%

$$\text{Potential energy exergy} \quad E_P = mgz \tag{6}$$

$$\text{Mechanical energy exergy} \quad E_W = E_K + E_P \tag{7}$$

The equation for the kinetic energy exergy of the exhaust system can be expressed as

$$E_K = q_m t\left(\frac{1}{2}c^2\right) \tag{8}$$

The heat exergy is the maximum useful work done by the heat to the outside world when a reversible thermodynamic process occurs between the heat whose temperature is higher than the ambient temperature and the environment. The maximum useful work done to the outside can be expressed as

$$\delta W_{\max} = \left(1 - \frac{T_0}{T}\right)\delta Q \tag{9}$$

According to the definition of exergy,$W_{\max}$ in Eq. (9) is the heat exergy in Q, which can be expressed as

$$E_Q = W_{\max} = \int \delta W_{\max} = \int\left(1 - \frac{T_0}{T}\right)\delta Q = Q - T_0\Delta S \tag{10}$$

where T_0 is absolute ambient temperature, T is the absolute temperature of heat, ΔS is the amount of entropy change which is numerically equal to $\int\frac{\delta Q}{T}$.

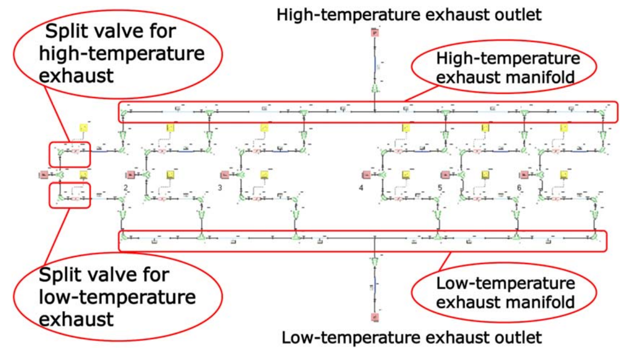

Fig. 5 Simulation model of exhaust piping system after energy splitting

Due to convection heat exchange and radiation heat exchange, results in part of the heat dissipation to the external environment, thereby resulting in the loss of exergy. According to Eqs. (11)–(14), the heat lost and the heat exergy lost in convective and radiant heat transfer processes can be expressed as

Heat loss by convective heat transfer

$$Q_D = \varnothing_D t = Ah(T - T_0)t \tag{11}$$

Heat loss by radiation heat exchange

$$Q_F = \varnothing_F t = A\sigma(T_w^4 - T_0^4)t \tag{12}$$

$$\text{Total heat loss} \quad Q = Q_D + Q_F \tag{13}$$

$$\text{Total heat exergy loss} \quad E_R = Q\left(1 - \frac{T_0}{T}\right) \tag{14}$$

where A is the heat exchange area, $\sigma = 5.67\times10^{-8}$ W/(m$^2\cdot$K^4), T_w is the wall temperature of the pipeline.

3.2 Evaluation Guidelines for the Exergy Analysis Method. From the second law of thermodynamics, it is known that in any irreversible process, the conversion of exergy to energy is bound to occur, so that the total exergy of the system is reduced. Therefore, unlike the energy conservation equation, the amount of exergy which the system input is not equal to the amount of exergy which the system output. And only when the exergy loss is added, the exergy balance equation can be established. The exergy balance equation of the system can be expressed as [23–25]

$$E_{H,in} + E_{Q,in} = E_{H,out} + E_{Q,out} + W + E_L \tag{15}$$

where $E_{H,in}$, $E_{H,out}$ are the enthalpy exergy of the input and output system; $E_{Q,in}$, $E_{Q,out}$ are the heat exergy of the input and output system; W is the mechanical work of the system output; and E_L is the exergy loss generated in the irreversible process.

It is not universal to evaluate the system by the amount of exergy the system output and the amount of exergy the system loss. In the actual thermodynamic calculation, it is often used to express the exergy transformation of the thermal system by the exergy efficiency η_e, the exergy loss coefficient ξ_e, and the exergy loss rate $e_{x,i}$.

The ratio between the input exergy and the output exergy, i.e., the ratio between the benefit exergy E_s and the cost exergy E_d, is exergy efficiency, which can be expressed as

$$\eta_e = \frac{E_s}{E_d}\times 100\% \tag{16}$$

The ratio between the input exergy and the local exergy loss is the exergy loss coefficient, which can be expressed as

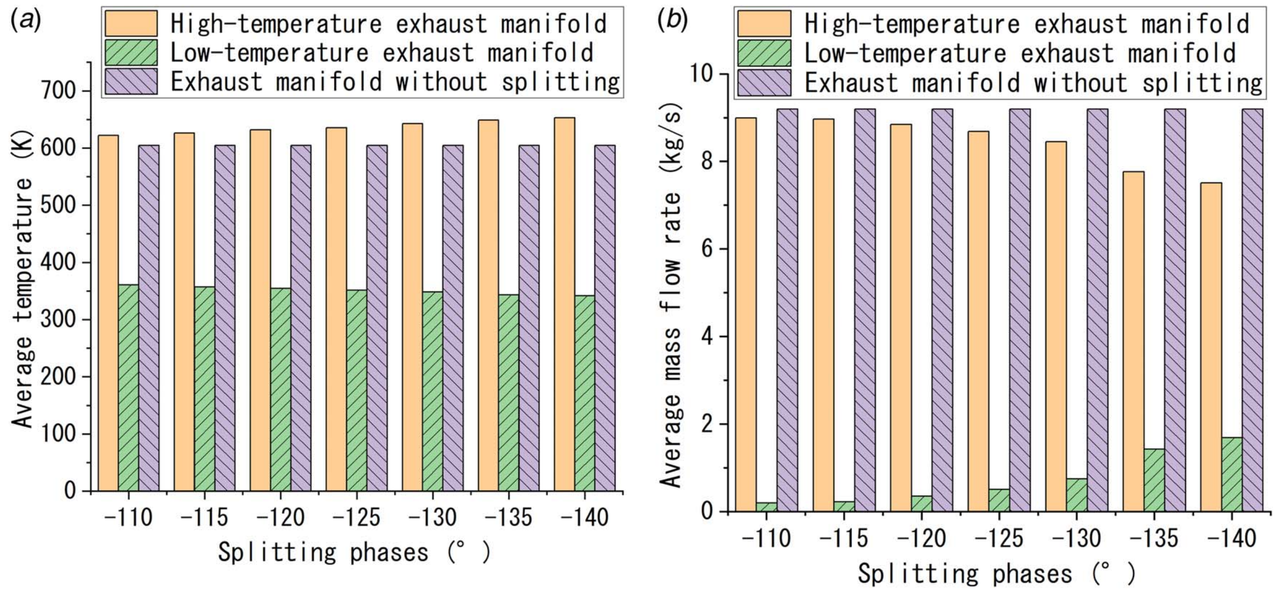

Fig. 6 (*a*) Average temperature and (*b*) average mass flowrate at the outlet of the exhaust pipe after energy spitting

$$\xi_e = \frac{\Pi_i}{E_d} \times 100\% \tag{17}$$

Based on the total system exergy loss $\sum \Pi_i$, the proportion of local exergy loss of a certain part Π_i is the exergy loss rate, which can be expressed as

$$e_{x,i} = \frac{\Pi_i}{\sum \Pi_i} \times 100\% \tag{18}$$

4 Results and Analysis

4.1 Analysis of Exhaust Parameters After Energy Splitting. The average temperature and average mass flowrate at the outlet of the high-temperature exhaust manifold and low-temperature exhaust manifold with different splitting phases obtained by simulation analysis are shown in Fig. 6.

From Fig. 6, it can be seen that there is an increase in the average temperature at the outlet of the high-temperature pipe of about 20–50 K after energy splitting. But there is a decrease in the mass flowrate at the outlet of the high-temperature pipe of about 0.2–1.69 kg/s. This leads to the conclusion that the total amount of exhaust gas decreases while the energy grade per unit quantity increases. In this case, it is not reasonable to prove the feasibility of the energy splitting system simply by the increase in temperature after energy splitting. Therefore, exergy analysis that takes both energy grade and energy quantity into account is needed to prove the effectiveness of the energy splitting system.

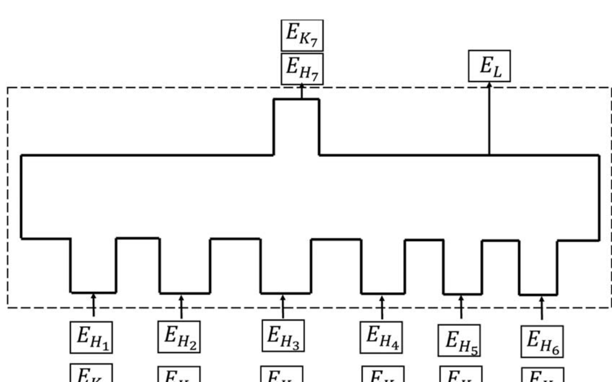

Fig. 7 Simplified model of the exhaust piping system of the low-speed diesel engine

4.2 Calculation and Analysis of the Exergy of the Exhaust System. The low-speed diesel engine exhaust piping system can be regarded as a stable flow opening system, and its simplified model is shown in Fig. 7, where E_{H_1}, E_{H_2}, E_{H_3}, E_{H_4}, E_{H_5}, E_{H_6} are the enthalpy exergy carried by the mass entering the system; E_{H_7} is the enthalpy exergy carried by the mass leaving the system; E_{K_1}, E_{K_2}, E_{K_3}, E_{K_4}, E_{K_5}, E_{K_6} are the kinetic energy exergy carried by the mass entering the system; E_{K_7} is the kinetic energy exergy carried by the mass leaving the system; and E_L is the heat exergy loss of the system due to heat dissipation.

The enthalpy exergy and enthalpy exergy loss coefficients of the system without energy splitting and with different splitting phases are shown in Fig. 8. From Fig. 8, it can be seen that under the splitting phase from −110 deg to −135 deg the enthalpy exergy of the system is greater than that of the traditional mode. And the enthalpy exergy loss coefficient of the system is smaller than that of the traditional mode, where the enthalpy exergy loss coefficient is the smallest at −115 deg, which is 0.101. And the enthalpy exergy of the system is the largest at this splitting phase, which is 1784.46 kJ. The reason for the reduction of enthalpy exergy loss coefficient is: long exhaust stroke and sweeping gas form are the characteristics of two-stroke diesel engine which result in high exhaust temperature and high exhaust energy grade in the early stage of exhausting and low exhaust temperature and low energy grade in the late stage of exhausting. If the normal exhaust mode is adopted, the high-temperature exhaust and low-temperature exhaust will be mixed in the manifolds. And the second law of thermodynamics shows that the heat transfer under the finite temperature difference is a typical irreversible process, and the irreversible process will bring entropy production, resulting in the loss of exergy. After taking the energy splitting, the high-temperature exhaust enters the high-temperature manifold and the low-temperature exhaust enters the low-temperature manifold, so that the mixing process of high-temperature gas and low-temperature gas will be weakened and the enthalpy exergy loss coefficient will be reduced. Although the use of energy splitting raises the exhaust temperature of high-temperature pipe, due to the fact that part of the exhaust gas enters the low-temperature

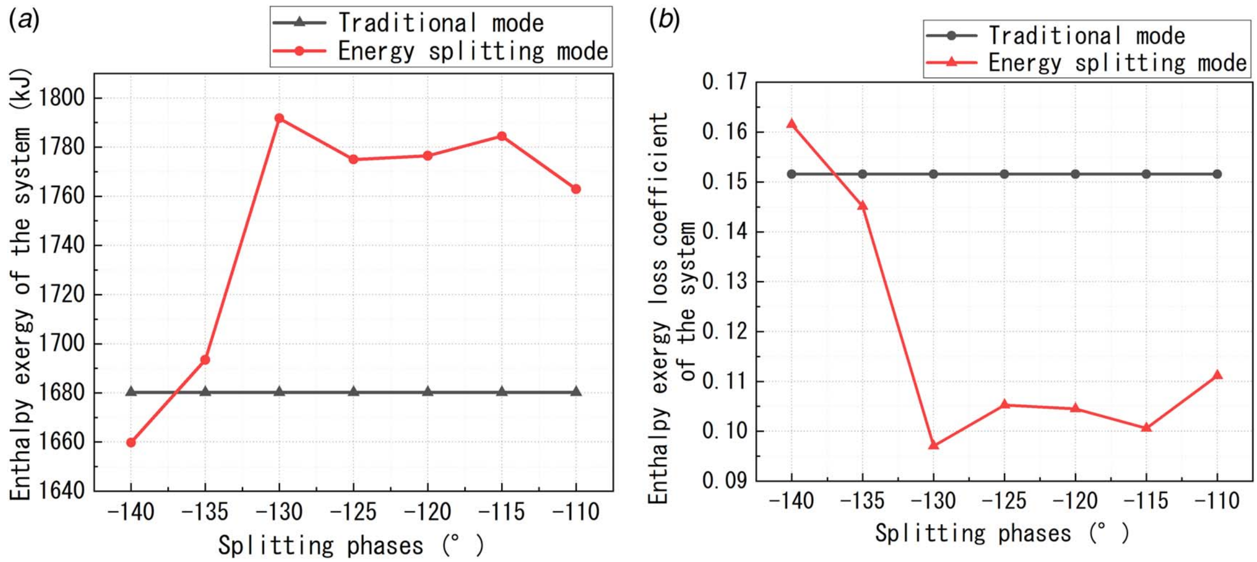

Fig. 8 Comparison of: (*a*) enthalpy exergy and (*b*) enthalpy exergy loss coefficients of the system before and after the energy splitting

collector, the mass flowrate of high-temperature manifold decreases. While the exhaust temperature of low-temperature pipe is lower than that without splitting, so the exergy of it decreases. Therefore, as shown in Fig. 8, if the splitting phase is too far forward, the total output enthalpy exergy will tend to fall instead of rising, so it is necessary to choose the right splitting phase.

The kinetic energy exergy of the system with different splitting phases and without energy splitting is shown in Fig. 9. As shown in Fig. 9, after the energy splitting the kinetic energy exergy is lower than that without splitting, and the more advanced the splitting phase is, the lower the kinetic energy exergy is. The reason is, after the energy splitting part of the exhaust gas enters the low-temperature exhaust manifold, so that the mass flowrate at the outlet of the high-temperature exhaust manifold decreases, then the kinetic energy exergy is reduced. While the mass flowrate at the outlet of the low-temperature exhaust manifold is very small, and the kinetic energy exergy is negligible, so the kinetic energy exergy after the energy splitting is reduced to some extent.

The total exergy efficiency of the system with different splitting phases and without energy splitting is shown in Fig. 10.

As shown in Fig. 10, the maximum exergy efficiency of the exhaust pipe is reached at −115 deg, which is about 0.872. So, splitting at −115 deg is the most valuable case for research in engineering practice. As shown in the results for −110 deg to −135 deg, the total exergy efficiency is increased after energy splitting. However, after energy splitting the total exergy efficiency can also be reduced, as shown in the results for −140 deg. In summary, the effect of energy splitting on the system's exergy efficiency needs further study.

5 Optimizations

5.1 Optimal Design of Exhaust Piping System Based on Heat Exergy. The heat loss and heat exergy loss of the exhaust piping system before and after energy splitting are shown in

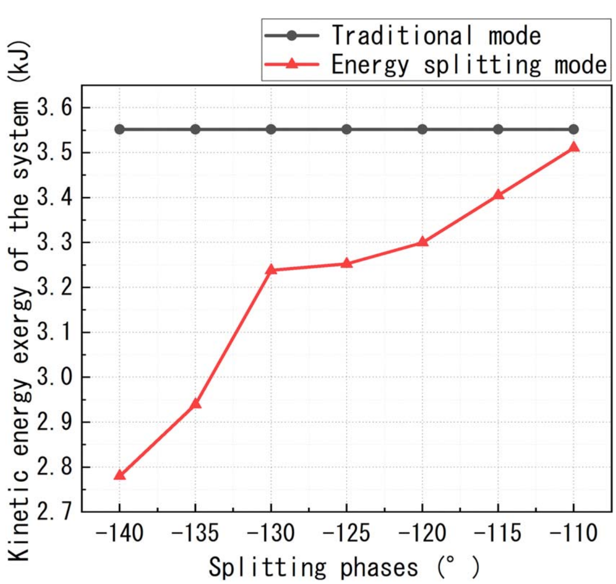

Fig. 9 Comparison of the kinetic energy exergy of the system before and after the energy splitting

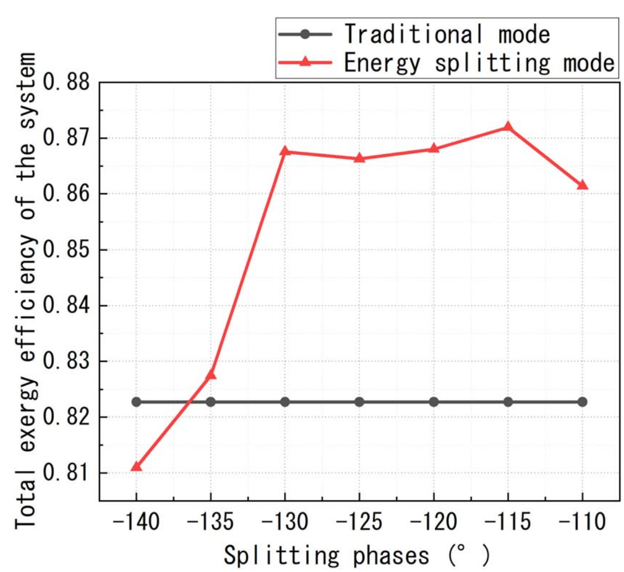

Fig. 10 Comparison of the system's total exergy efficiency before and after energy splitting

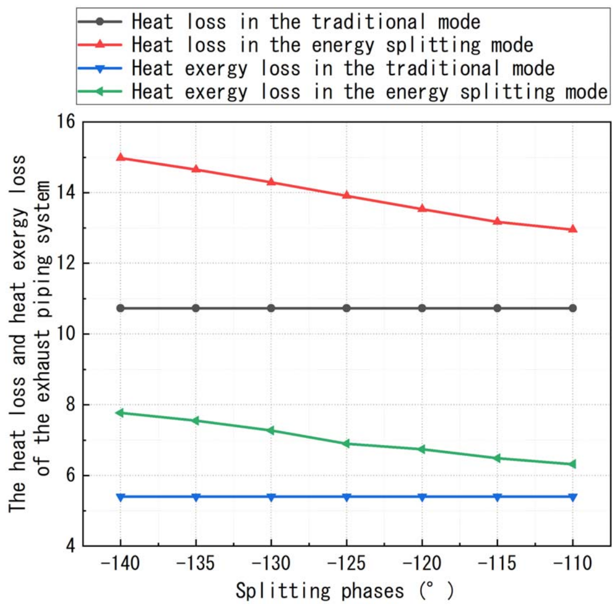

Fig. 11 Comparison of the heat loss and the heat exergy loss of the system before and after energy splitting

Fig. 11. As shown in Fig. 11, the heat loss and heat exergy loss due to heat dissipation after energy splitting are higher than in the traditional mode. The reason is that the high-temperature exhaust flows in the high-temperature manifold after energy splitting, so the temperature of the wall of the high-temperature manifold is higher than that of the traditional mode. And the temperature difference between the outer wall of the high-temperature manifold and the environment increases, so the heat loss increases. At the same time, according to the second law of thermodynamics, it is known that the same amount of heat, the higher the temperature is, the more exergy contains. Therefore, because the high-temperature manifold loses more heat with higher temperature after energy splitting, the heat loss caused by heat dissipation after energy splitting will be larger than the situation before energy splitting. And the temperature of exhaust in the high-temperature manifold will be higher as the splitting phase is advanced. The temperature of the outer wall of the high-temperature manifold will also rise, and the heat loss caused by heat dissipation will be larger.

In actual engineering, the ship pipeline is usually covered with a layer of insulation material to prevent heat loss. In order to weaken the heat exergy loss caused by heat dissipation, this paper covers a layer of rock wool on the outer surface of the manifolds.

After calculation, the heat exergy loss and exergy efficiency of traditional mode and energy splitting mode with insulation covering can be obtained and compared with the case of no insulation covering on the manifolds. The results are shown in Fig. 12. As shown in Fig. 12, after covering the insulation material, the temperature of the outer wall drops significantly resulting in a significant reduction in the temperature difference between the exhaust pipe system and the surrounding environment. And the heat exergy loss due to heat dissipation from the pipe wall is significantly reduced compared to the heat exergy loss before covering the insulation material. After covering the insulation material, the heat exergy loss caused by heat dissipation from the pipe wall in the energy splitting mode is very little different from that before energy splitting. So, the heat exergy loss caused by energy splitting can be ignored in the case of covering the insulation material. Since the heat exergy dissipation of the system is reduced after covering the insulation material, the total heat exergy efficiency of the system without energy splitting and the total heat exergy efficiency of the system with energy splitting are both increased to a certain extent compared with that without covering the insulation material. And the splitting phase of the highest heat exergy efficiency is still at −115 deg.

5.2 Optimal Design of Exhaust Piping System Based on Kinetic Energy Exergy. The piping parameters used in the simulation model of energy splitting built in Flowmaster software are same as the traditional mode. This is not reasonable, because the parameters of the original piping are designed according to the mass flowrate in the traditional mode, and the designed volume meets the volume requirement in the traditional mode. However, since the mass flowrate of the exhaust which flows into the high-temperature manifold is reduced after energy splitting, and at the same time, the mass flowrate of the exhaust which flows into the low-temperature manifold is very small. It is not reasonable to design the energy splitting system according to the

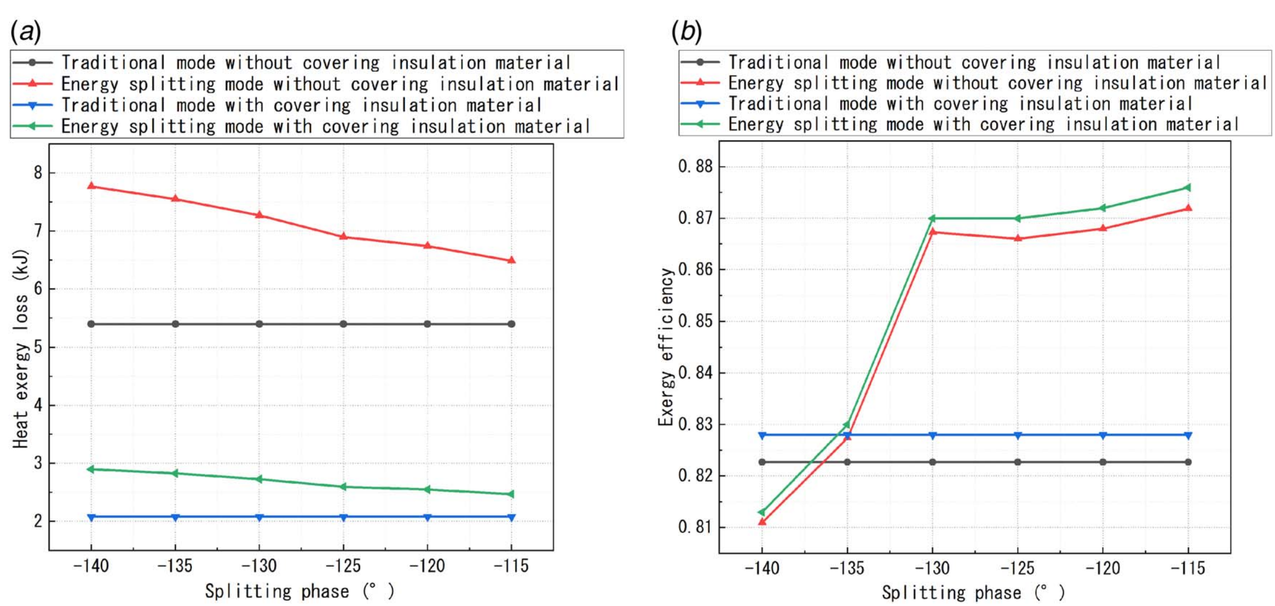

Fig. 12 Comparison of (*a*) heat exergy loss and (*b*) exergy efficiency of the system before and after covering the insulation material

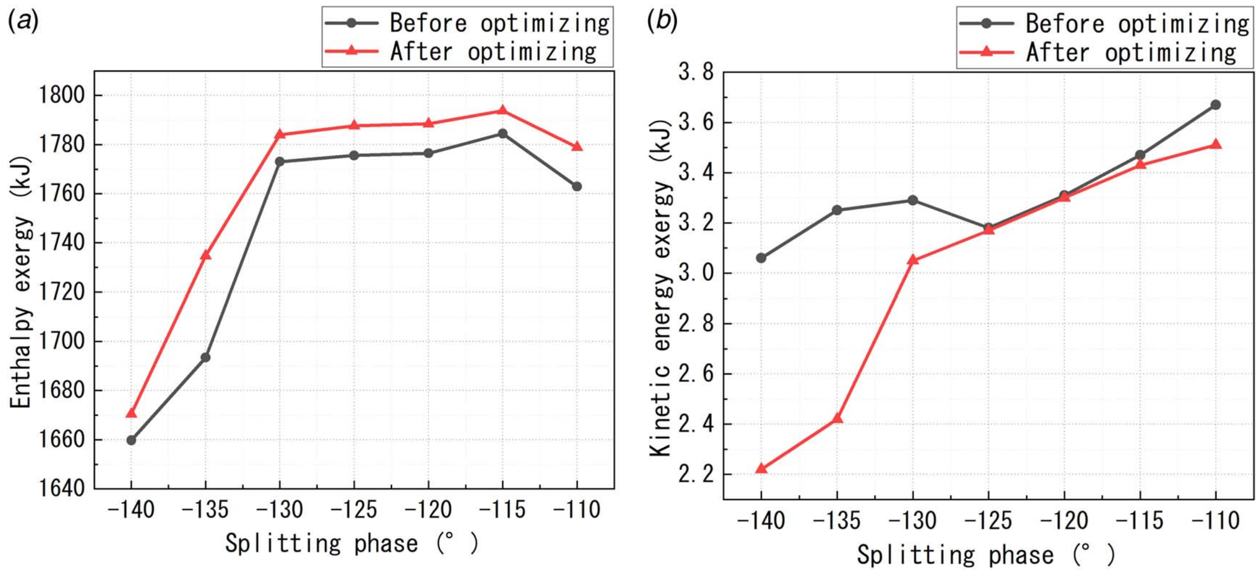

Fig. 13 Comparison of (*a*) enthalpy exergy and (*b*) kinetic energy exergy of the system before and after optimizing

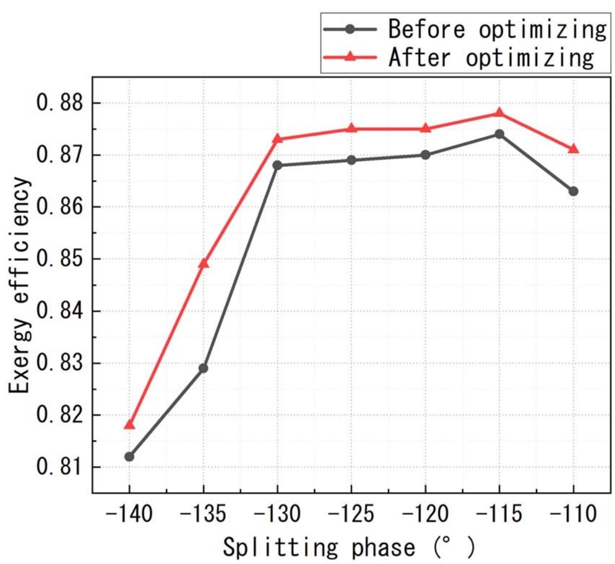

Fig. 14 Comparison of exergy efficiency of the system before and after optimizing

original size. Therefore, the design of the piping diameter needs to be optimized.

According to the mass flowrate, the manifold diameter is optimized for different splitting phases with reasonable volume. After the optimization, the original splitting phase is used in Flowmaster software to perform simulation analysis.

The enthalpy exergy and kinetic energy exergy after optimization are calculated and compared with the results before optimizing. The results are shown in Fig. 13. From Fig. 13, it can be seen that the enthalpy exergy and kinetic energy exergy are increased compared with those before optimizing.

After the calculation, the exergy efficiency of the system after optimizing the piping diameter is compared with that before optimizing, and the results are shown in Fig. 14. As shown in Fig. 14, the exergy efficiency of the system after optimizing the piping diameter is increased by 0.4–2% compared with that before optimization, and the maximum exergy efficiency of the system after optimizing the piping diameter is also obtained at −115 deg splitting phase.

6 Conclusions

This paper proposes a method of improving the exhaust energy grade which is called exhaust energy splitting. Different from the traditional exhausting mode, the exhaust energy splitting technology splits the high-temperature and high-pressure exhaust and the low-temperature and low-pressure sweeping gas, and recovers them separately. GT-Power software and Flowmaster software are co-simulated to build the model of exhaust energy splitting system. Exergy analysis is used to analyze and prove the feasibility of the exhaust energy splitting system. Also, to improve the exhaust energy splitting system, it is optimized from the perspectives of heat exergy and kinetic energy exergy. The following conclusions are obtained:

(1) The exhaust energy splitting technology realizes flexible utilization of exhaust energy in the whole phase range, and truly realizes "optimal use of heat". After energy splitting, the exhaust temperature of high-temperature pipe is increased by about 20–50 K, which greatly improves the energy grade of the exhaust.
(2) Through exergy analysis of the exhaust system after energy splitting, it is proved that exhaust energy splitting technology not only increases the average temperature of exhaust gas of the high-temperature manifold, but also effectively improves the exergy efficiency of the exhaust system. Through the comparative analysis between the systems under different splitting phases, the exergy efficiency of the system is increased by about 0.47–4.92%. And the exergy efficiency of the system reaches the maximum at −115 deg splitting phase, which is 87%. This provides a reference for the control of energy splitting valve.
(3) To optimize the exhaust energy splitting system from the perspective of heat exergy, a layer of insulation material is covered on the outer surface of the manifolds. After covering the insulation material, the heat exergy loss of the system with energy splitting is decreased by about 4.02–4.87 kJ, and the exergy efficiency is increased by about 0.2–0.41%.
(4) To optimize the exhaust energy splitting system from the perspective of kinetic energy exergy, the diameter of the exhaust piping is designed again. After optimizing the diameter of the exhaust piping, the exergy efficiency of the system with energy splitting is increased by about 0.4–2%. And the best exergy efficiency is also reached at −115 deg splitting phase.

(5) Through the exergy analysis of the exhaust energy splitting system, the energy grade and exergy of exhaust after energy splitting are increased. Therefore, the exhaust energy splitting technology has great significance for WHR systems, such as ORC systems.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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